REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE Jan 2001	3. REPORT TYPE AND DATES COVERED FINAL 17 Jul 95 - 16 Jan 99

4. TITLE AND SUBTITLE
Multicasting and Security Services for Next-Generation Gigabit Local Lightwave Networks

5. FUNDING NUMBERS
DAAH04-95-1-0487

6. AUTHOR(S)
Biswanath Mukherjee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California - Davis

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 34636.1-RT-AAS

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Emerging high-bandwidth networking applications and an increasing number of users on the Internet are strong indicators that our next generation of networks much employ very-high-speed "bitways". Fortunately, lightwave networks employing wavelength-division multiplexing (WDM) do provide the necessary high-speed backbone where the huge fiber bandwidth is carved up into a number of nonoverlapping wavelength channels, each of which can be operated at electronic speed, e.g., a few Gbps, and which, as a result, can be accessed directly by end-users. WDM optical networks are now becoming commercial. At Davis, we have been researching architectures for WDM optical networks. Specifically, we have found that multicasting, which is an emerging important networking application, can be naturally accommodated by the broadcast-and-select variety of local lightwave networks. Our research supported by this agreement has produced many new and important results in multicasting, as summarized below. Unfortunately, our investigation on anti-sniffing security measures in local lightwave networks was not as successful.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

- [ ] Reprint (Orig + 2 copies)
- [ ] Technical Report (Orig + 2 copies)
- [ ] Manuscript (1 copy)
- [x] Final Progress Report (Orig + 2 copies)
- [ ] Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: DAAH04-95-1-0587

REPORT TITLE: Multicasting and Security Services for Next-Generation Gigabit Local Lightwave Networks

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Meshell Hays

Meshell Hays for Biswanath Mukherjee
Business Manager
University of California, Davis
Department of Computer Science
530-752-0415
hays@cs.ucdavis.edu

Multicasting and Security Services for Next-Generation Gigabit Local Lightwave Networks

Final Technical Report
Research Agreement No. DAAH04-95-1-0487

Biswanath Mukherjee
Department of Computer Science
University of California
Davis, CA 95616

Tel: (530) 752-4826; 752-7004
Fax: (530) 752-4767
E-mail: *mukherje@cs.ucdavis.edu*

January 2001

Abstract

Emerging high-bandwidth networking applications and an increasing number of users on the Internet are strong indicators that our next generation of networks much employ very-high-speed "bitways". Fortunately, lightwave networks employing wavelength-division multiplexing (WDM) do provide the necessary high-speed backbone where the huge fiber bandwidth is carved up into a number of nonoverlapping wavelength channels, each of which can be operated at electronic speed, e.g., a few Gbps, and which, as a result, can be accessed directly by end-users. WDM optical networks are now becoming commercial. At Davis, we have been researching architectures for WDM optical networks. Specifically, we have found that multicasting, which is an emerging important networking application, can be naturally accommodated by the broadcast-and-select variety of local lightwave networks. Our research supported by this agreement has produced many new and important results in multicasting, as summarized below. Unfortunately, our investigation on anti-sniffing security measures in local lightwave networks was not as successful.

1 Introduction

Communication networks of tomorrow will need to provide and manage large amounts of bandwidth in order to support the requirements of multimedia applications such as video conferencing, video-on-demand, and the world wide web. Optical networks are a logical choice to meet these demands because of the huge potential bandwidth that optical fiber has to offer, with capacities on the order of 25,000 gigahertz. The primary challenge in deploying optical networks is finding a way to efficiently utilize the bandwidth of fiber in order to provide high levels of service to the end user. One promising method of managing the high bandwidth of optical fiber is wavelength-division multiplexing (WDM). In WDM, channels are created by dividing the bandwidth into a number of wavelength or frequency bands. In order to take advantage of the potential of WDM, we must be able to design efficient architectures and protocols based on current optical device technology.

In WDM networks, stations are equipped with a number of transmitters and receivers. The transmitters consist of lasers which are modulated to transmit data. They may either transmit at a single fixed wavelength, or they may be tunable over a range of wavelengths. Receivers typically consist of photodetectors, and they may also be either fixed to receive on a single channel, or tunable to receive over a range of channels. Because of the high cost of tunable components, practical architectures are usually limited to a single tunable transmitter and single tunable receiver. In some architectures, tunable transmitters and receivers may be supplemented with fixed components, while in other architectures, only fixed components are used. Because the number of tunable transmitters and receivers at each node is limited, protocols must take full advantage of the tunability provided, and must also ensure that transmitter, receiver, and channel resources in the network are being utilized efficiently.

One type of service which efficiently utilizes network resources is multicasting. Multicasting is the transmission of data from a single source node to multiple destination nodes in a manner that attempts to minimize the consumption of network resources. Networks without multicasting support must rely on multiple one-to-one communications for sending data from a single source to multiple destinations. These multiple transmissions may waste transmitter resources at the source node as well as channel resources in the network. With multicasting support, the source node may send a single transmission which is then broadcast to multiple destinations or forwarded from one destination to another, thus conserving transmitter and channel resources.

In this study, we investigate WDM local area network architectures and protocols which are based on the passive star coupler. Our results are summarized in the following sections.

2 Multicast Partitioning

In modern networks, the high demand for bandwidth and quality of service requires the efficient utilization of network resources. These resources include transmitters, receivers, and communication links (channels) in the network. One method of conserving these network assets is through the use of multicast communications or multicasting.

Multicasting is the transmission of data from a single source to multiple destinations in a way that attempts to minimize the consumption of network resources. Many applications, such as teleconferencing, video distribution, and e-mail lists can exploit multicast support. Traditionally, networks have supported unicast transmissions in which a single source may transmit data to a single destination. However, if a message is intended for multiple destinations, sending a separate transmission to each destination may be an inefficient use of resources. Instead, by using multicasting, a source might send only a single transmission which is then broadcast to multiple destinations or forwarded from one destination to another, thus reducing the amount of transmitter resources used at the source.

Methods for implementing multicasting in networks have been gaining much attention in recent years. Most previous efforts have focused on the multihop multicasting problem. In a multihop network, a data packet may traverse a number of links and a number of intermediate nodes before reaching its destination. The multihop multicasting problem is to construct a minimal cost tree which is rooted at the source node and spans all of the destination nodes. The cost of the tree is determined by the amount of network resources consumed, such as the number of links in the tree. This problem has traditionally been formulated as the Steiner Minimal Tree problem which has been shown to be NP-complete.

A problem that has received less attention is the single-hop multicasting problem. In a single-hop network, data is transmitted directly from the source node to the destination node without traversing any intermediate nodes. Single-hop multicasting can be viewed as a special case of multihop multicasting in which the multicast tree has a depth of one and in which there may be additional constraints of timing and coordination. Since single-hop optical networks are based on a broadcast medium, multiple destinations may receive the same transmission, thereby reducing the number of times that a message is transmitted. For the case in which only a single channel is used in the broadcast medium, e.g., Ethernet, the problem becomes trivial, since each station is able to receive all transmissions that take place on the medium. However, when the broadcast medium is expanded to accommodate multiple channels, such as in a wavelength-division multiplexing (WDM) network, the destination nodes may be listening to a channel other than the channel on which the source node is transmitting the multicast message. Therefore, there is the additional problem of coordinating the source node and the destination nodes such that they are tuned to the appropriate channel during a transmission. The single-hop multicasting problem in a multiple channel network is then to schedule a message in a way which ensures that each of the destinations receives the message while also minimizing the total amount of resources being used.

In [1], we study the single-hop multicast problem as applied to a WDM passive star coupler network. In such a network, nodes are connected via fiber to a star coupler, a passive broadcast device. The fiber bandwidth is divided into a number of optical channels, with each channel assigned a unique wavelength. The channels are accessed by nodes through the use of tunable transmitters and receivers. Tunable transmitters and receivers can access any channel in the system by tuning to that channel, but may selectively access only a single channel at any given time. Transmissions on each channel are broadcast by the star coupler to all nodes, and a node may receive transmissions by tuning its receiver to the appropriate channel at the appropriate time. For handling a multicast transmission, a source must coordinate with all of the destinations of its message in a way which ensures that each of the destinations receives the message. This problem has been addressed in a few previous works.

In [1], we show that it may be more efficient for a node to transmit a message multiple times to subsets of the multicast group rather than transmitting the message a single time to the entire multicast group. Each of these subgroups would consist of the receivers in the multicast group that became available within a certain range of time. An earlier subgroup of the multicast group would receive an earlier transmission from the source node, while a later subgroup would receive a separate transmission some time later. This reduces the amount of time that receivers in the earlier subgroup have to wait in order to receive the transmission.

3 Multiconfiguration Multihop Protocols

In a PSC-based WDM network, a transmission on any channel is broadcast to every node in the network. A node may receive the transmission by tuning its receiver to the appropriate channel in which each of N nodes has a fixed-tuned transmitter operating on its own unique wavelength channel and a tunable receiver which can receive from any of the N channels numbered $\omega_1, \omega_2, \cdots, \omega_N$). Thus, communication between nodes requires some amount of coordination. This coordination is provided by the network protocol.

Protocols for PSC networks are typically classified as either single-hop or multihop. The basic goal of the protocol is to provide a certain degree of connectivity among the nodes in order to enable communications. A single-hop protocol typically achieves connectivity through the use of tunable components. In a sense, a single-hop network achieves full connectivity (a fully-connected logical topology) among nodes, since each node can communicate *directly* with every other node by appropriately tuning its transmitters or receivers; however, each such connectivity is only meaningfully established for the packet transmission duration. A limitation of single-hop networks is that they may incur significant overhead due to the high tuning times of tunable components. Typical transceiver tuning times may range from tens of microseconds to a few milliseconds, depending on the technology employed; thus, a tuning period may be on the order of several packet transmission times. A multihop network achieves connectivity through the use of additional transmitters and receivers at each node and typically requires no tuning, instead relying on a static logical topology. Since a multihop network doesn't rely on tuning, it doesn't incur the potentially high tuning overhead of a single-hop network. On the other hand, a multihop network's reliance on multiple transmitters and receivers, combined with the expense of such components, often results in low connectivity in the network, and, consequently, higher average hop distances.

In [2], we consider a class of protocols called multiconfiguration multihop protocols (MMPs). These protocols are multihop protocols which not only rely on the number of transmitters and receivers to achieve a desired connectivity, but also *make use of tuning to increase connectivity.* These protocols use tunable components to cycle through a fixed number of configurations[1], and the logical topology of the network is then defined in the time domain over all of these configurations. Using tuning in this manner, we can increase the logical connectivity of the network, thus reducing the average hop distance at the expense of additional tuning requirements.

4 A Multicast Protocol for Local Lightwave Nets

A wavelength-division multiplexed (WDM) based multicasting protocol for a single-hop broadcast-and-select local optical network is proposed in [3]. In particular, our approach employs a control-channel-based media-access protocol that schedules multicast packets, while incorporating arbitrary transceiver tuning times and propagation delays. A number of data channels (W) supply communication bandwidth to N nodes, where $N > W$, while the control channel is used for synchronization and scheduling. Each node is equipped with one fixed transmitter and one fixed receiver on the control channel, as well as one tunable transmitter and one or more tunable receivers for data channel access. The protocol takes advantage of the broadcast nature of a control channel by storing information of the system state of the network at each node. This allows efficient distributed scheduling of multicast packets. The metric of receiver throughput is defined to measure the expected number of busy receivers at steady state. Simulation results suggest that WDM single-hop multicasting experiences highest receiver throughput performance when multicast size is either small or very large, and when nodes are equipped with multiple receivers.

In Laxman-PEval, we present an approximate analytical solution for the average packet delay in a local lightwave network, which employs the Multicast Scheduling Algorithm (MSA) [3] as its medium-access control (MAC) protocol. First, we develop an approximate analytical solution for the probability distribution of the receiver busy time. We demonstrate and explain some interesting and unobvious behavior of this distribution. Then, using the receiver busy time distribution, we calculate the maximum receiver throughput and the average packet delay. Results from the analytical solution match very well with those obtained from simulation.

[1] We define a configuration as the topology of the network at a given point in time as determined by the state of the tunable components in the network.

5 Students Supported

This research supported the PhD research [5] of Dr. Jason P. Jue, who graduated in June 1999 and joined the Computer Science Department at University of Texas, Dallas, as an Assistant Professor.

It also partly supported the research of another PhD student (Dr. Michael S. Borella, currently Member of Technical Staff, 3Com Corp.) and the PI.

References

[1] J. P. Jue and B. Mukherjee, "The advantages of partitioning multicast transmissions in a single-hop optical WDM network," *Photonic Network Communications Journal*, vol. 1, no. 2, pp. 111-124, Aug. 1999. (See also *IEEE International Conference on Communications (ICC '97)*, Montreal, Canada, pp. 427-431, June 1997.)

[2] J. P. Jue and B. Mukherjee, "Multiconfiguration Multihop Protocols (MMPs): A New Class of Protocols for Packet-Switched WDM Optical Networks," *IEEE/ACM Transactions on Networking*, to appear (Oct. 2000). (See also *Proc., IEEE Infocom '98*, San Francisco, CA, pp. 816-823, April 1998.)

[3] M. Borella and B. Mukherjee, "A Multicasting Protocol for Multichannel Local Optical Networks," Invited Book Chapter in *Optical WDM Networks: Principles and Practice*, Ed: K. M. Sivalingam and S. Subramaniam, Kluwer Academic Publishers, March 2000. (See also *Proc., IEEE International Conference on Communications (ICC '95)*, Seattle, WA, pp. 1277-1281, June 1995.)

[4] L. H. Sahasrabuddhe and B. Mukherjee, "Probability Distribution of the Receiver Busy Time in a Multicasting Local Lightwave Network," *Performance Evaluation Journal*, vol. 33, no. 3, pp. 149-173, Aug. 1998. (See also *Proc., IEEE International Conference on Communications (ICC '97)*, Montreal, Canada, pp. 116-120, June 1997.)

[5] Jason Jue, *Design and Analysis of Architectures and Protocols for WDM Optical Networks*, Ph.D. Dissertation, Department of Electrical and Computer Engineering, University of California, Davis, June 1999.